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A numerical model of a solar domestic hot water system integrating hybrid photovoltaic/thermal collectors

Pierrick Haurant[a,b] , Christophe Ménézo[a,b], Leon Gaillard[a,b], Patrick Dupeyrat[c] *

[a]*Centre Thermique de Lyon (CETHIL UMR CNRS 5008 / INSA Lyon / UCB Lyon 1), 69621 Villeurbanne,France*
[b]*Chaire INSA/EDF « Habitats and Energy Innovations », 69621 Villeurbanne, France*
[c]*EDF R&D, Département Enerbat, 77818 Moret sur Loing, France*

Abstract

A Photovoltaic-Thermal (PV-T) module is a solar hybrid collector which converts part of incident solar energy into electricity and recovers a fraction of the remainder dissipated as heat.
A new high efficiency, covered, water PV-T component was developed in the context of a partnership between CETHIL, Fraunhofer ISE and EDF R&D. Tested under controlled conditions, the module demonstrated unparalleled electrical and thermal efficiencies. Within the framework of the project PHOTOTHERM an array of modules was integrated into a domestic hot water system installed on the BESTLab laboratory at EDF R&D, France, so that the performance of a complete system could be monitored under real conditions. In parallel, a numerical model was developed taking into account the heterogeneity of PV cell temperature, and the geometrical complexity of the Fractherm® heat exchanger developed by Fraunhofer ISE. The model, developed in TRNYS, was validated for steady state and transient conditions. The aim of the work now is to assess the energetic and exergetic performance of systems integrating this new PV-T module.
The PV-T prototype, as well as the entire domestic hot water system, and the complete TRNSYS model are presented in this paper. Model validation was performed using measurements taken under real conditions. The model allows a rapid energetic analysis of the domestic hot water system.

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Keywords: Photovoltaic-Thermal hybrid module; Domestic hot water system; TRNSYS model

* Corresponding author. Tel.: +33 (0) 4 79 75 86 21.
E-mail address: christophe.menezo@univ-smb.fr

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1. Introduction

Hybrid PV-T collectors have become the object of renewed interest in recent years with the development of low or positive energy buildings. New multifunctional envelope types are needed in order to meet all the energetic needs of such buildings, and PV-T technologies are interesting because to generate simultaneously heat and electricity for various applications (domestic hot water, solar cooling). Moreover, they convert a higher part of the solar energy received than standard PV pannels by recovering the heat generated.

In this context the PHOTOTHERM project was launched upon a collaboration between EDF R&D and the CETHIL laboratory. Its first aim is to evaluate the potential of PV-T systems by studying precisely their behaviour as part of a solar domestic hot water (SDHW) system in real conditions. The long-term aim is to show the optimal conditions of use of PV-T panels.

Nomenclature

T_{cons}	set point temperature, °C	T_w	Water temperature, °C
γ	control function	t	time
ΔT_+	upper dead band, ° C	ΔT_-	lower dead band, °C
T_{PV}	PV cells temperature, °C	T_{ref}	reference temperature, °C
η_{ref}	reference PV yield	η_T	PV yield at temperature T
β	PV yield loss coefficient		

2. Experimental installation

2.1. Domestic hot water system

Within the framework of the PHOTOTHERM project, a PV-T SDHW system was constructed and instrumented on the site of BESTLab (Building Envelope & Solar Technologies Laboratory), EDF R&D, France (Fig. 1). The sizing of the domestic hot water system was been determined following the recommendations of [1] for the paris region for a daily consumption of 150 l.

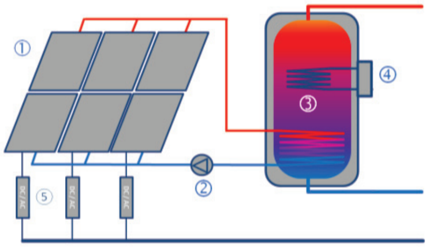


Fig. 1. Hot water domestic Installation. 1) PV-T field- 2) Pump - 3) Hot water tank - 4) Auxiliary heater- 5) micro-inverter

The installation comprises 6 PV-T panels of 1 m^2, facing south, tilted by 45°, 2 by 2 electrically in series and connected to micro-inverters to inject the electrical power into the grid. The PV-T panels are placed pair wise in parallel in the hydraulic system and a pump works as an on-off controller. The maximum volumetric flow rate of the heat transfer fluid is 4 l/min in a closed-circuit. The circuit contains 300 l and has an electrical heating auxiliary of 2.4 kW so that the heated water follows the set point temperature of 55 °C. A safety controller for the solar array is fixed to 100 °C. Lastly, a water consumption profile was imposed corresponding to a classical demand of domestic hot water for a family of 4 people based on the L-cycle in accordance with Pr EN255 (Fig. 2).

Regarding system monitoring, the environmental measures (total in-plane radiation, outdoor temperature and wind speed), the flow rate, glycol water temperature along the hydraulic loop, generated electrical power and the energy consumption of the water storage tank auxiliary heater are measured on a minute-wise basis starting from 1st September 2012.

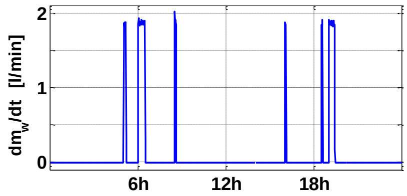


Fig. 2. Fixed profile of water consumption (6 September 2013)

2.2. PV-T Prototype

The aim of the hot water storage installation presented is to study the behaviour of the PV-T pannels integrated into a complete system. For each of the 6 panels, four rows of eight PV monocrystaline cells (156 x 156 x 0.2 mm) were electrically connected in series, inserted between two EVA (Ethylene-vinyl acetate) films of thickness 0.46 mm. This layer was plced on the flat surface of a fractal rollbond type heat exchanger (of size 1350 x 750 mm) followed by a layer of f-polymer film 0.13 mm thick. The resulting sandwich was laminated together under temperature, pression and vaccum conditions similar to the lamination conditions of PV conventional modules. The assembled PV-T absorber was inserted into a metal frame with an insulation layer located on the backside. On the front side, non-reflecting glass with a transmission coefficient above 0.94 was placed 20 mm in front of the PV cells to provide a narrow an air gap (Figure 2). The design of the collectors aswell as the material selection are detailed by Dupeyrat et al. [2-4].

The thermal performance of the prototype PV-T modules were tested under controlled conditions (radiation, ambient temperature, wind) at Fraunhofer ISE. Measurement were undetaken in accordance with the norm EN12975 adapted to characterize the collector for a hybrid mode [5]. Radiation was simulated by close array of spot lights affording an incident radaition intensity of 938 W/m^2. Ventilation was maintainedd to simulate a constant wind speed of 3 m/s. A thermal reference efficiency of 83.4 % for an open circuit was obtained for a purely thermal use of the collector. If a hybrid use of the collector is required(PV + thermal) a reference efficiency of 72.8 % has been obtained for an electrical efficiency of 10.5 %. Under real conditions, the performance was evaluated for the first working week of the SHDW operation (September 2012). An electrical efficiency of 8.5 % was reported for a overrall thermal efficiency of 36 % [6].

3. Modeling the domestic hot water system

3.1. TRNSYS Model

This SDHW system has been modelled with TRNSYS, following a similar arrangement to previous works [1, 7-10]. TRNSYS a dynamic simulation tool particularly dedicated to the modelling of energetic complex systems at the system scale. The software adopts an approach where a system is reduced to a set of interconnected subsystems modelled as TYPES. In our case, the entire system has been modelled using TYPES available in the TRNSYS standard library sumarised in table 1 and as illustrated in figure 3.

The model includes the following numerical limitations and settings:

- the weather data and the consumption profiles allow minute-wise simulations;
- the TYPE used to simulate the PV-T modules does not work for a zero flow. A residual flow of 7 l/h was therefore imposed;
- mass conservation at pipe diameter shifts was ensured via “equation” components as shown in the diagram;
- $\Delta T_+ = 7$ °C et $\Delta T_+ = 4$ °C delimits the upper and lower bounds of the dead band ot the controller:

$$\begin{cases}\gamma_t = 0 \text{ si } T_w < T_{cons} + \Delta T_+ \text{ and } \gamma_{t-1} = 0\\ \gamma_t = 0 \text{ si } T_w < T_{cons} - \Delta T_- \text{ and } \gamma_{t-1} = 1\\ \gamma_t = 1 \text{ si } T_w > T_{cons} + \Delta T_+ \text{ and } \gamma_{t-1} = 0\\ \gamma_t = 1 \text{ si } T_w > T_{cons} + \Delta T_+ \text{ and } \gamma_{t-1} = 1\end{cases} \quad (1)$$

T_{cons} is the set point temperature (55 °C in our case) and T_w the water temperature at the bottom of the tank;

- temperature stratification in the tank was modeled in the TYPE 60d. In our case, a sensitivity study enabled us to restrict to 10 the number of nodes defining the temperature profile relative to the height in the tank.

Table 1. Elements of the loop and TYPES used in the hot domestic water model

Elements	Type	Comment
Weather data	9	Weather data on site, at a minute time step
Pipe	31	Complete Hydraulic loop
PV-T pannel	50	Florschuetz model [11]
Pump	3d	Constant flow pump
Controller	2b	Hysteresis controller
Consumption	9	Profil implemented *in situ*
Domestic hot water tank	60d	With auxiliary heating

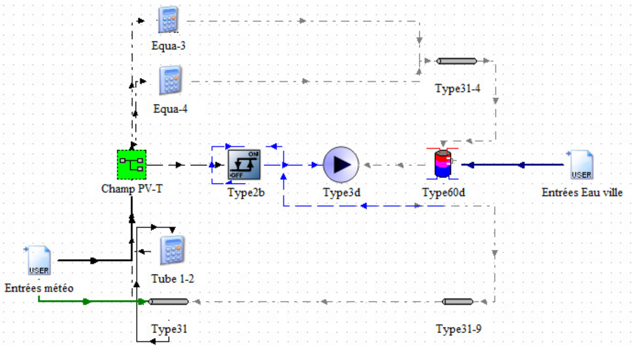


Fig. 3. TRNSYS model of a PV-T SDHW system

3.2. Model validation

The first six days of data were used validation the model, from the 2nd until the 7th September 2015. Figure 4 presents the variation in water temperature at different heights in the domestic hot water tank. It also presents the spiked demands of the auxiliary tank heater. A significant stratification of the water in the tank is clearly observed. Differences of 25 – 30 °C were observed in the water tank between the bottom (inlet tap water) and the top tank (outlet heated water) (figure 4). At the top of the tank the water temperature remains steady because the auxiliary heater affects the water temperature at the node located 0.96 m above the lowest level of the tank. At this node temperature variations between 55 °C and 48 °C are observed in phase with the highest spiked power. The variation in the temperature of water at the bottom of the tank (at 0.6 and 0.26 m high) is dominated by the refilling of the tank. The other nodes shown in figure 4 are seen to increase during the day: these nodes are impacted by the energetic contributions of the water tank heat exchanger where the heated glycol water flows through the PV-T panels during the day. The thermal behavior of the water stored in the tank, which is not monitored, seems coherent with these results.

The simulated power were found to follow a similar trend to the measured power. The powers simulated and measured take place at closed moments (Fig. 4 bottom). The energy consumption profiles during this test period are quite similar but the energy consumed obtained by simulation is higher than the measured energy during the two last days (Fig. 5).

The model was found to predict glycol water temperature at the entrance of the PV-T panels to an accuracy better than 1°C. These temperatures represent also the temperatures at the output of the heat exchanger. We can confirm that, the energy exchanges at the bottom of the water tank are well modelled (Fig. 7 below). The output and input PV-T simulated and measured temperatures are similar, showing that the simulation results agree with the measured temperatures.

The measured glycol water temperature at the output of the collector exhibits large variations over short timescales, which are not reproduceded by the simulation (top of Fig. 7). This abrupt bevahiour is linked to the pump control: at certain moments of the day the pump stopped, letting the glycol water stagnate for a few minutes in the PV-T collectors. During this time the temperature of the water in the PV-T panels rises considerably. The pump was configured to stop running when the bottom temperature of the tank exceeds the output temperature of the PV-T collectors. This behaviour is not systematically reproduced by the model. The daily starting and stopping time of the pump are similar between the simulation and the data, but the simulation assumes that the pump is switched on throughout the day without interruption (Fig. 7 below).

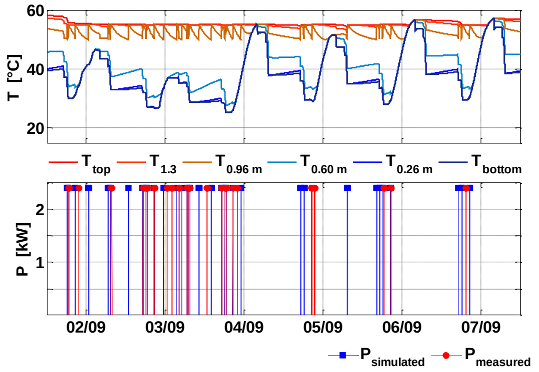


Fig. 4. Temperature evolutions at different heights and stratification in the tank (at the top) and the power of the auxiliary heating

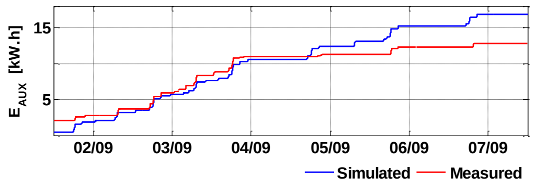
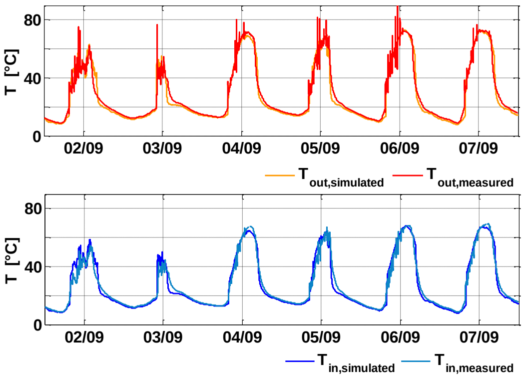


Fig. 5. Consumed electrical energy by the auxiliary heat



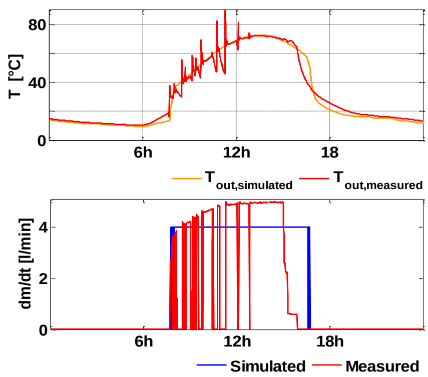


Fig. 6. Input temperatures (bottom figure) and output temperatures (top figure) of the glycol fluid PV-T collectors

Fig. 7. Output PV-T panel temperatures (top) and mass flow rate (bellow) the 6th September 2013

The PV measured and simulated electrical power are presented bellow in figure 8. The electrical model of type 50 considers a linear decrease of the PV cell electrical efficiency η_T versus their temperature T_{PV} according to:

$$\eta_T = \eta_{ref}\left(1-\beta\left(T_{PV}-T_{ref}\right)\right) \tag{2}$$

With η_{ref} the reference efficiency of the PV cells PV at reference temperature T_{ref}.

It is apparent from figure 8 that TYPE 50 does not provide an adequate simulation of electrical power at certain times of day. Indeed spurious values are observed at the start and end of most days in the simulation, which corresponds to times when the flow rate is close to zero. At other times of day the calculated electrical power falls considerably below the measured power generation. For example, at midday on 4th and 6th September, the power calculated is 300 W whereas 500 W were actually produced. In summary, even though the presented model using TYPE 50 gives coherent results for the thremal behaviour of the PV-T system, the simulation of electrical power is unsatisfactory.

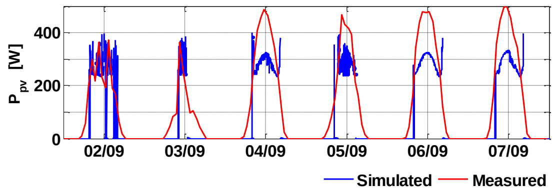


Fig. 8. Produced electrical power of PV-T collectors

4. Conclusions

An experimental domestic solar hot water system integrating hybrid PV-T module prototypes has been installed and monitored during 18 months on BESTLab site of EDF R&D. Its aim was to follow the behaviour of these prototypes within a complete system in order to evaluate its real performance the value added compared to more conventional solutions.

In this paper, a TRNSYS simulation has been compared to monitoring data from the test rig at BESTLab. The thermal behaviour of each sub-system, PV-T modules and tank in particularly, have been validated, showing calculated temperatures in general agreement with the data. Comparing power and energy consumed by the auxiliary heating suggests the control systems has been correctly simulated by the model. Finally, this model allowed to point out the limitations of the PV-T model currently in use, (TYPE 50), in particular with regards electrical power generation and for close to zero glycol water flow rates. This confirms the need to implement a TYPE based upon the more sophisitcated transient three dimensional thermal model presented in [12].

Acknowledgements

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